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EFFECTS OF PREDATOR CONTROL ON THE SURVIVAL AND BREEDING SUCCESS OF THE ENDANGERED HAWAIIAN DARK-RUMPED PETREL

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Abstract. Haleakalā, Maui, hosts the world's largest known nesting colony of endangered Hawaiian Dark-rumped Petrels (*Pterodroma phaeopygia sandwichensis*), or 'Ua'u, with about 900 known nests. In 1979, introduced predators were identified as significant limiting factors for the Hawaiian Dark-rumped Petrel at Haleakalā National Park. Small Indian mongooses (*Herpestes auropunctatus*) were identified as major predators, with cats (*Felis catus*) being secondary. In 1981, the National Park Service implemented an extensive trapping program to protect the Hawaiian Dark-rumped Petrel colony and outlying areas from predators. Since then, about 300 live traps of various sizes have been monitored.

This paper expands on a 1993 National Park Service study comparing reproductive success before and after trapping, and in areas protected and unprotected from predators. Significant differences in nesting activity and nesting success varied from year to year. In all years except two, protected sites showed significantly higher nesting activity and success. This suggests that predator control has a positive effect on protecting the Hawaiian Dark-rumped Petrel nesting habitat.

Key Words: Dark-rumped Petrel; endangered species; Haleakalā birds; Hawaiian Petrel; predation; predator control; seabird breeding success; seabird management; 'Ua'u.

There are two subspecies of Dark-rumped Petrels (*Pterodroma phaeopygia*): the Hawaiian Dark-rumped Petrel (*P. p. sandwichensis*), and the Galápagos Dark-rumped Petrel (*P. p. phaeopygia*). Both are endangered under the federal Endangered Species Act of 1973. The Hawaiian Dark-rumped Petrel, hereafter referred to by its Hawaiian name 'Ua'u, was once numerous throughout the Hawaiian Islands. Munro (1955) refers to comments by people on the island of Moloka'i of 'Ua'u arriving at Pelekunu Valley in numbers large enough to darken the sky. Populations are now confined to higher elevations (Banko 1980d).

Habitat loss, predation, and hunting are major causes of endangerment of the world's island birds (King 1984). In Hawai'i, several species of introduced mammals contributed to the decline of native bird populations (Moors and Atkinson 1984, Stone 1989, Bailey and Kaiser 1993, Seto 1994, Seto and Conant 1996). Introduced herbivores, such as cattle and goats, browse on vegetation in seabird colonies and often trample nests. On island ecosystems such as Hawai'i, mammalian predators feast on seabirds that have, for the most part, evolved in predator-free environments. The effects of an individual predator, such as a small Indian mongoose (*Herpestes auropunctatus*), can be extremely destructive to a population of colony-nesting seabirds (Simons 1983, Bartle et al. 1993). Most seabirds are long-lived and have low adult mortality, delayed maturity, small clutch sizes, long nesting periods, and low annual productivity. Continuous predation of breeding adults by an individual predator can cause extinction of a seabird population. Seabird life-history patterns prevent rapid replacement of depredated adults (Moors and Atkinson 1984, Simons 1984).

Natural and unnatural events affect the reproductive success of seabirds. Natural events include climate changes such as El Niño events (Wilson 1991, Ribic et al. 1992, Duffy 1993), direct and indirect disturbance by native predators (Tomkins 1985, Furness and Monaghan 1987, Reichel and Glass 1989, Paine et al. 1990, Burness and Morris 1993), and competition with other seabird species (Furness and Monaghan 1987, Harrison 1990). Unnatural events, such as habitat degradation and loss, predation by introduced predators, and direct and indirect disturbance by humans, are extremely detrimental to seabird breeding success (Simons 1983, Feare 1984, Vermeer and Rankin 1984, Atkinson 1985, Litvinenko 1993, Bailey and Kaiser 1993, Seto 1994, Seto and Conant 1996).

Olson and James (1982a) found fossil evidence of breeding 'Ua'u near sea level. It appears that Polynesian activities in lowland areas exterminated 'Ua'u populations before European arrival to the Hawaiian Islands. Predation by dogs (*Canis familiaris*), pigs (*Sus scrofa*), and Polynesian rats (*Rattus exulans*) introduced by the Polynesians (see van Riper and Scott *this volume*) further decreased the numbers of 'Ua'u. However, the primary cause of 'Ua'u decline may have been the large-scale harvest of the chicks by the Polynesians, as evident by abundant fossils found in middens and lava tubes (Olson and James 1982a, Moniz 1997). The Polynesians considered ‘Ua‘u nestlings a delicacy for exclusive consumption by chiefs (Henshaw 1902a). Each season, the chiefs sent hunters to retrieve these delicacies. Hunters used dogs to locate ‘Ua‘u nests in the early 1900s (Kramer 1971). They inserted sticks into the burrows then twisted the stick to become entangled into the downy feathers of the chicks. The chicks were then easily pulled out of the nests and taken.

European arrival to the islands in the late 1700s brought the introduction of additional predators including roof rats (*Rattus rattus*), Norway rats (*R. norwegicus*), cats (*Felis catus*), and more dogs. Rats have been identified as predators of burrow-nesting seabirds. On Midway Atoll, Hawai‘i, roof rats preyed upon Bonin Petrel (*Pterodroma hypoleuca*) eggs significantly decreasing Bonin Petrel reproductive success (Seto 1994, Seto and Conant 1996).

In 1883 sugar planters brought the small Indian mongoose to Hawai‘i to control rats in the cane fields (Kramer 1971). Simons (1983) identified mongooses as the primary predator of the ‘Ua‘u. In 1979, he observed high rates of predation (34% of active burrows) and initiated a trapping scheme to remove this predator from the Haleakalā colony.

Europeans introduced, in the late 1700s to 1800s, several domesticated animals as gifts to the Hawaiian royalty (Kramer 1971). Cattle (*Bos taurus*), horses (*Equus caballos*), sheep (*Ovis aries*), and goats (*Capra hircus*) were released into the wild. The Hawaiian royalty protected these animals with a kapu (forbidding law), much to the detriment of the Hawaiian environment and the already shrinking seabird habitat. Newcomers also introduced game animals such as the European wild boar (*Sus scrofa*), axis deer (*Axis axis*), and mouflon sheep (*Ovis musimon*) to Hawai‘i, compounding the habitat alteration.

There is no documentation that feral goats or pigs prey upon ‘Ua‘u. However, together with other introduced herbivores, these animals cause indirect negative affects on the ‘Ua‘u. These herbivores devastated Hawai‘i’s natural landscape by overgrazing and accelerated erosion by trampling over the landscape (Haleakalā National Park, unpubl. data). Simons (1983) noted negative effects of goats and pigs on ‘Ua‘u nesting areas. Goats chose bedding sites on or near ‘Ua‘u burrows and caused burrows to collapse. Furness (1988) found that sheep (*Ovis* sp.) and elk (*Cervus elaphus*) preyed upon tern and skua chicks living on Foula, Shetland. Pigs in the Galápagos destroyed petrel burrows by rooting and preyed upon both birds and eggs (Harris 1970).

The known surviving populations of ‘Ua‘u are probably nesting in suboptimal high-elevation habitat. Maui (Krushelnycky et al. *this volume*) and Hawai‘i (Hu et al. *this volume*) are the only Hawaiian Islands with known active ‘Ua‘u nests. Currently, about 95% of the known breeding population occur in and around Haleakalā Crater of Haleakalā National Park on the island of Maui (Fig. 1). About 50 nests are on the island of Hawai‘i at the higher elevations of Hawai‘i Volcanoes National Park on Mauna Loa (Hu et al. *this volume*; D. Hu, pers. comm.). Although nests have not been found, a nesting population of ‘Ua‘u is thought to exist on Kaua‘i (Ainley et. al 1997a; B. Cooper and R. Day, unpubl. report). ‘Ua‘u have been heard on the islands of Lāna‘i and Moloka‘i, but nests have not yet been found (Simons 1983).

On Maui, J. Larson (unpubl. report) conducted the initial studies in 1967 that identified and mapped the first ‘Ua‘u burrows near the summit of Haleakalā. From 1968 to 1980, J. Kunioki (unpubl. report) found and observed about 400 of the 900 known burrows that are now monitored. His work was limited to the summer months and did not include the fledgling season. Simons (1983) from 1979 to 1981 was the first to conduct comprehensive monitoring of ‘Ua‘u nests throughout the entire breeding season. Nest checks were continued by W. Han from 1982 through 1984 (unpubl. report).

Simons (1983) trapped extensively for predators in the ‘Ua‘u colony from 1979 through 1981. In 1981, the National Park Service expanded upon Simons’ initial predator trapping program to include much of the western area outside the primary ‘Ua‘u colony. Since then, live traps of various sizes have been checked and baited on a weekly basis.

Haleakalā National Park began regular, thorough monitoring of ‘Ua‘u nests in 1988. Nests were checked at least once a month from mid-February through the end of October. Monitoring efforts were concentrated in the inner west rim of Haleakalā Crater. Other areas were visited as time and personnel allowed. Visits to these peripheral subcolonies were sometimes limited to once or twice during the entire breeding season.

Haleakalā National Park initiated construction of a boundary fence in 1976. The goal was to protect the park’s ecosystems from feral animals, particularly pigs and goats. The fence is made of 1.2-m high hog wire, with two strands of barbed wire running parallel to the top of the hog wire. The maximum height of the fence is 1.5 m. Approximate mesh size is 15 cm^2. Since completion of the boundary fence around the Crater District of the park in 1988, goat and pig populations have been reduced to zero, with occasional ingress of animals. These vagrant ani-

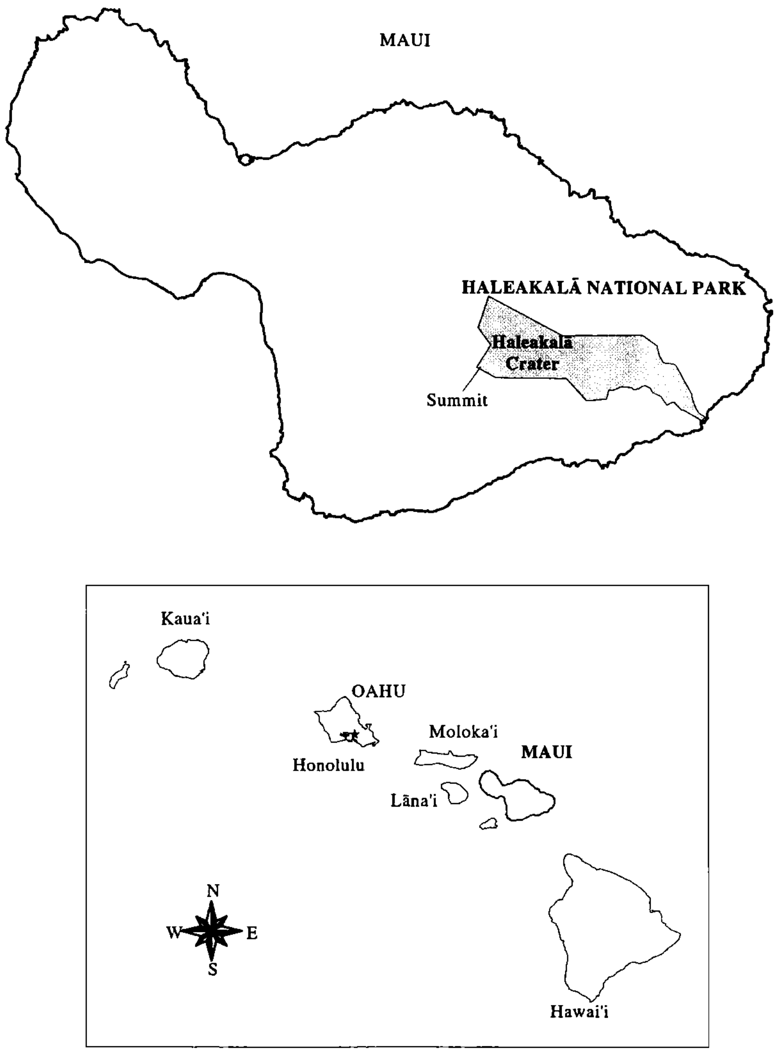

FIGURE 1. Major Hawaiian Islands and Haleakalā National Park on the island of Maui.

mals are immediately removed when found (Haleakalā National Park, unpubl. data).

In 1993, Hodges (1994) conducted a study to determine the effectiveness of predator control on the breeding success of the 'Ua'u. This study found that predator control has a positive effect on 'Ua'u breeding success and survival. The study also found that habitat protection through feral animal fencing and eradication may provide additional protection for the 'Ua'u nesting colony.

In this paper, we further examine the effects of predator control on 'Ua'u nesting activity and success. We also make inferences on the effects of feral ungulate control on 'U'au nesting. We utilize all available data collected from previous years.

METHODS

STUDY SITE

Mount Haleakalā is a dormant shield volcano that defines east Maui and is over half the land mass of the island of Maui. Haleakalā National Park extends from sea level to the 3,055 m summit of Mount Haleakalā (Fig. 1). Haleakalā Crater is a large erosional depression, about 1,000 m deep, and is about half the land area of Haleakalā National Park.

The highest concentration of 'Ua'u nests are along the inside west rim of Haleakalā Crater from about 2,400 to 3,055 m above sea level (Fig. 2). Other nests are in other locations of the crater and along the outer west slope. The nesting habitat consists of large boulders, rocky outcrops, and cinder fields (Simons 1983, Brandt et al. 1995). Vegetation is still sparse (probably resulting from almost 200 years of feral herbivore

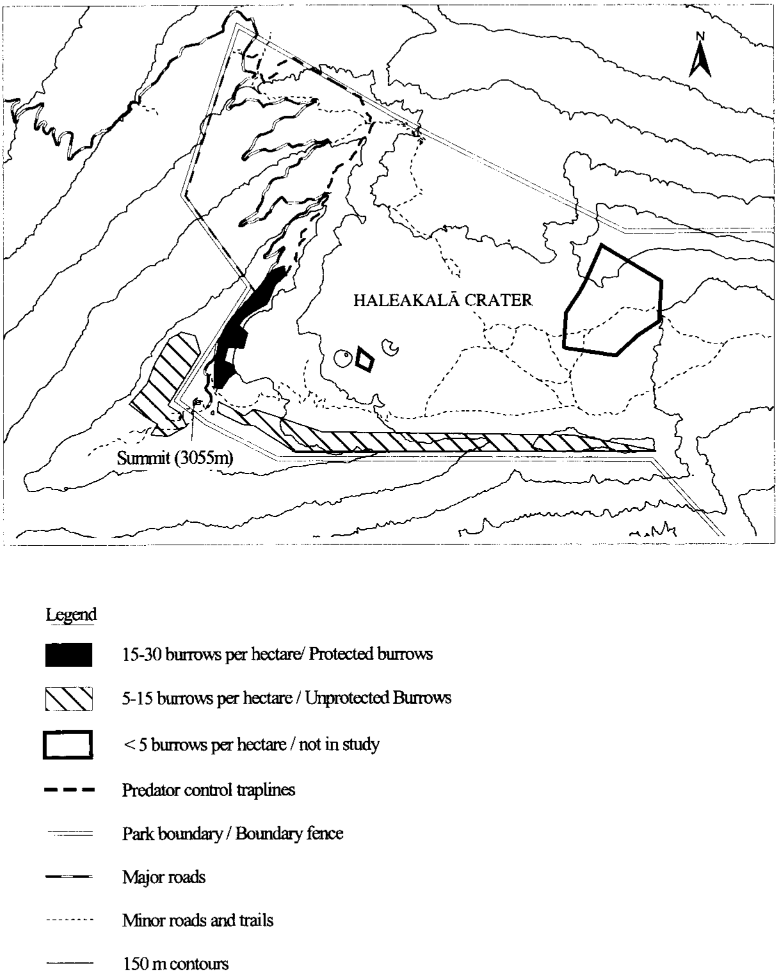

FIGURE 2. Location of ‘Ua‘u burrows, predator control traps, and fences.

browsing) and consists of native shrubs and bunch grass. Shrubs are within 0.1 to 5 m of ‘Ua‘u burrows.

Predator Control

There are about 300 live traps protecting the ‘Ua‘u and the endangered Hawaiian Goose or Nēnē (*Branta sandvicensis*) populations of Haleakalā National Park (Fig. 2). Traps are along the park's boundary, road sides, ridge tops, hiking trails, pathways where predators have been sighted, and near buildings. Sixty-eight traps are directly within the ‘Ua‘u colony, while the remaining traps are at lower elevations outside the colony (Fig. 2). We use live traps as a precaution against accidental capture of the ground-nesting ‘Ua‘u and Nēnē. Both birds have been caught in these traps (Haleakalā National Park, unpubl. data).

Predator control has been continuous since 1981. Information on predator catch was used as a measure of predator activity inside and outside the ‘Ua‘u colony. We calculate catch per trap day from all trapping information collected from 1981 to 1996 to examine trends in predator catch.

Nest Monitoring

‘Ua‘u are at the Haleakalā colony from mid-February through late November (Simons 1983; Haleakalā National Park, unpubl. data). Nests were checked during these months.

Nests were monitored using direct and indirect methods. Direct methods involved viewing nests by looking through the burrow entrance or other opening to the nest chamber with a flashlight, or by use of a remote camera. Indirect methods involved placing toothpicks, about 2.5 cm apart, at the burrow entrance and recording any signs of ‘Ua‘u activity. Simons (1983) and Hodges (1994) found that the indirect method of using toothpicks was as valid at determining nesting activity and nesting success as were direct methods. Prior to the start of each season and after

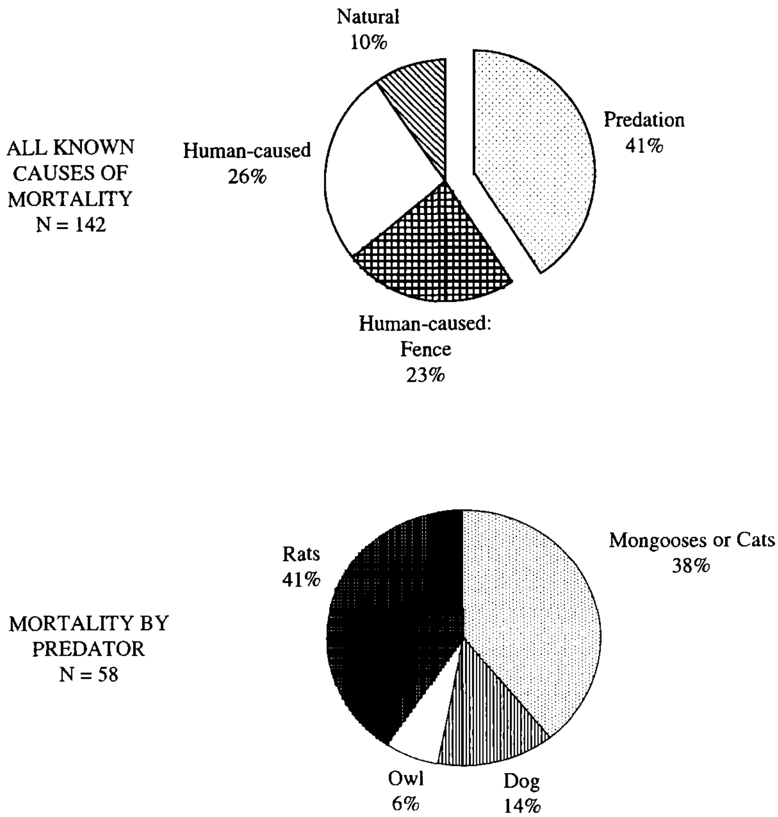

FIGURE 3. Known causes of 'Ua'u mortality 1964–1996.

every burrow check, each burrow was cleared of all signs of 'Ua'u activity.

We classified each burrow as "entered" or "not entered" by 'Ua'u. Adult 'Ua'u weigh about 435 g, the body size of a small chicken, and have a wing span of about 98 cm (Simons 1983). 'Ua'u leave prominent foot prints and guano at the burrow entrances. Nests were considered "entered" by 'Ua'u if at least three consecutive toothpicks were displaced during subsequent checks and foot prints or guano were evident. "Not entered" were those burrows with all toothpicks intact, or displacement of single or alternate toothpicks (i.e., down, up, down). The distinction between intact and alternately displaced toothpicks were recorded as possible rat entries may occur. In addition, any signs of activity (evidence of burrow excavation, feathers, eggshells, etc.) in and near the burrow were noted.

We determined the final status of each nest at the end of each season. Burrows that were "entered" for three or more checks throughout the season were considered "active." Simons (1983) indicated that failed and nonbreeders depart by mid-September. 'Ua'u chicks exiting burrows prior to fledging leave large amounts of downy feathers in front of nests (Simons 1983, Hodges 1994). Burrows were documented as "fledged chick" if "active" after 15 September and downy feathers were present at the burrow entrance.

Nesting Activity and Success

To determine the effectiveness of the predator control program, we compared nesting activity and nesting success between protected and unprotected sites (Fig. 2). Protected sites were near predator control traps. Unprotected sites were those not in protected areas. Although the southeastern colony lies within the park's boundary fence, we considered those nests unprotected since traps have never been placed in that area. The fence mesh is large enough for easy entry to the colony by mongooses, cats, and rats.

Numbers of burrows surveyed and frequency of checks varied from year to year. We used all available data from 1982, when traps were placed in the 'Ua'u colony, to 1996 to determine the effectiveness of predator control.

Data from 7- to 10-day checks indicated that monthly checks were as accurate as 7- to 10-day checks to determine nesting activity. Burrow checks occurring twice a month were as accurate as 7- to 10-day checks to determine nesting success. (See below for definitions of nesting activity and nesting success.) We therefore used data from burrows that were checked at least once month from February through September, and twice a month from September through November. We also used data from years where at least 30 bur-

TABLE 1. COMPARISON OF NESTING ACTIVITY AND NESTING SUCCESS OF 'UA'U BETWEEN PROTECTED AND UNPROTECTED SITES

Year	Nesting activity (%)			Nesting success (%)		
	Protected	Unprotected	P[a]	Protected	Unprotected	P[a]
1982	37.25	35.00	0.074	32.73	0	0.002
1990	78.13	80.00	0.082	49.18	10.00	0.0006
1991	69.70	53.09	0.003	48.64	25.58	0.003
1992	54.96	23.08	<0.001	16.97	15.15	0.79
1993	66.47	33.68	<0.001	38.19	32.81	0.414
1994	43.45	35.46	0.09	23.01	44.00	0.002
1995	75.00	64.71	0.11	50.00	31.82	0.03
1996	70.39	88.17	0.001	46.73	28.05	0.009

[a] P-value derived from chi-square and Fisher's exact tests comparing protected and unprotected nests.

rows per site were checked. Years with sufficient data on 'Ua'u nests surveyed for both the protected and unprotected sites were 1982 and 1990 through 1996.

Simons (1983) found that nesting activity is a good indicator of 'Ua'u population health. We defined nesting activity as the proportion of burrows surveyed that show signs of burrow activity. We defined nesting success as the proportion of active burrows that show signs of fledging chicks. Nesting activity and success were compared between protected and unprotected sites using chi-square test and the Fisher exact test for comparing two proportions (Zar 1984).

MORTALITIES

Information on 'Ua'u mortalities is available from 1964 to 1996. All carcasses or abandoned eggs were examined and cause of mortality was identified when possible. From 1992 to 1996, prior to the return of 'Ua'u to the crater each year, all areas were cleared of 'Ua'u carcasses and abandoned eggs. Causes of mortality were placed into one of four categories: (1) natural causes; (2) human-caused; (3) human-caused by fence; and (4) predation. Mortality by natural causes included death due to old age, eggs pushed out of nests that were not disturbed by predators, 'Ua'u flying into rocky outcrops, etc. Human-caused mortality included road kills, caved-in burrows, collision into human-built structures, etc. We defined the boundary fence as a separate category (human-caused by fence) of human-caused mortality to identify the impact of the boundary fence, and to modify the fence to decrease 'Ua'u mortality. Mortality from predation and all other causes were compared.

PREDATION IDENTIFICATION

Characteristics of predation by each type of predator have been identified (Simons 1983, Tomkins 1985, Hodges 1994). We used these characteristics to identify predation by mongoose, dog, cat, rat, or owl on the 'Ua'u. Mongooses punctured a small hole on the side of the egg, licked out the contents of the egg, punctured the back of the bird's neck, and possibly decapitated adults. Dogs scattered limbs and feathers over a wide area and mutilated carcasses. Cats crunched the back of the 'Ua'u skull and left both wings attached to a slightly chewed carcass stripped of most flesh (often called a "bridle carcass"). Rats left remnants of unevenly chewed pieces of eggshell, moved eggs out of burrows, drank or ate the contents, and abandoned the almost empty shell. Rats also dragged chick carcasses from the burrows to sheltered areas (called 'ratteries') where food debris including petrel bones, accumulated. Rats left fresh droppings at burrows of missing chicks, and the vegetation platforms used as 'Ua'u nests were scattered. Owls neatly plucked the 'Ua'u body and usually only ate viscera and pectoral muscles.

RESULTS

NESTING ACTIVITY

Five of eight years showed significant differences in nesting activity between protected and unprotected sites (Table 1). Years with significant differences ($P < 0.10$) were 1991, 1992, 1993, 1994, and 1996. In all years except 1996, nesting activity was significantly higher in protected sites.

NESTING SUCCESS

Six of eight years showed significant differences in nesting success between protected and unprotected sites (Table 1). Years with significant differences ($P < 0.10$) were 1982, 1990, 1991, 1994, 1995, and 1996. In all years except 1994, nesting success was significantly higher in protected sites.

MORTALITIES

Data from 1964 through 1996 indicate 230 documented mortalities of birds and eggs with 142 having known causes. Predation accounted for 41% of all known mortalities (Fig. 3). Of these instances of predation, 41% were rats, 39% were cats or mongooses, 14% were dogs, and 6% were owls.

Human-caused mortalities accounted for 49% of all known mortalities (Fig. 3). These mortalities were due primarily to collision with human structures such as poles, buildings, vehicles, lights, and fences. The park's boundary fences accounted for 23% of all mortalities. Ten percent of all mortalities were from natural causes.

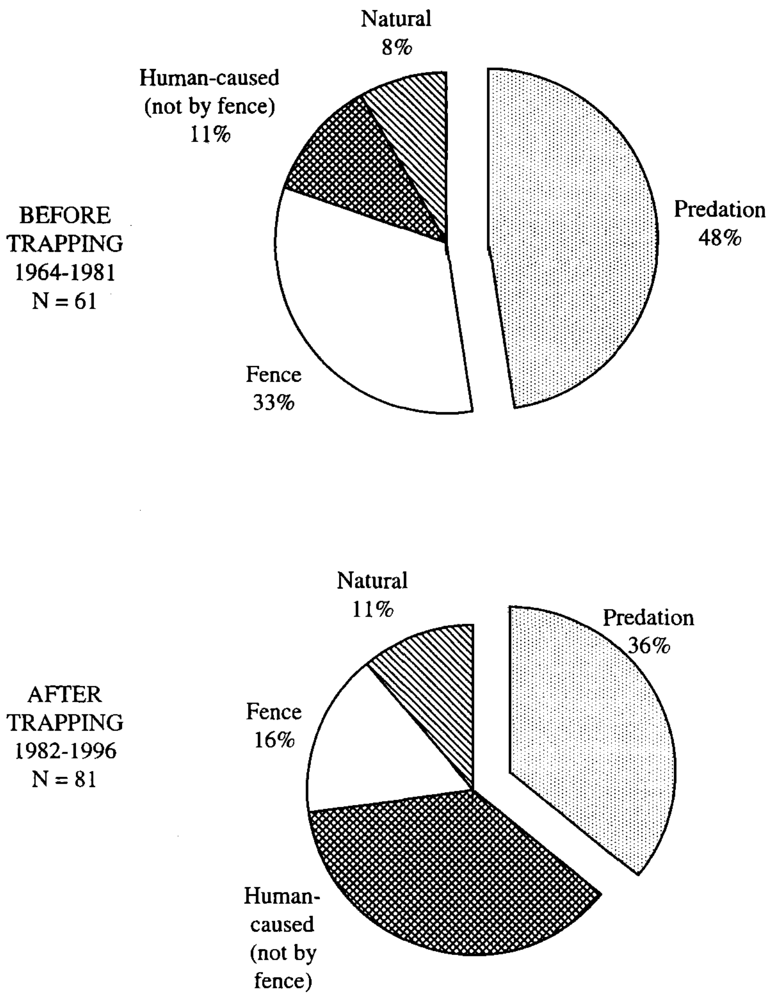

FIGURE 4. Causes of ‘Ua‘u mortality before and after trapping.

Comparison of mortalities before (1964–1981) and after (1982–1996) trapping indicates that known instances of predation decreased from 48% of all known mortalities (Fig. 4; N = 61) to 36% (N = 81). However, there was no significant difference between predation and other causes of mortality before and after trapping (P = 0.159).

Since the inception of the predator control trapline, there have been only seven instances of cat and mongoose predation in 15 years. Instances of predation by other predators (rats, dogs, owls) remain minimal (25 in 15 years), but still persist. Dog predation was relatively high from 1990 to 1993 (4, 2, 2, and 1 instance per year, respectively) with all instances occurring outside the park's fence and in a colony that is adjacent to a state of Hawai‘i public hunting area. Gut content analysis of one dog caught in that area revealed ‘Ua‘u remains.

Predator Catch and Activity

The majority of catches from the traps within the ‘Ua‘u colony were rats (Fig. 5). Data from traplines outside the ‘Ua‘u colony are useful for determining the source of predators to the ‘Ua‘u colony. Rat catches were higher outside the colony, but have been consistent for the past 15 years (Fig. 6). This suggests that rats persist within the colony and that trapping simply keeps rat populations from increasing.

Mongooses and cats were caught at very low numbers both in and outside the ‘Ua‘u colony, but they were caught at higher rates outside the colony (Fig. 6). Inside the colony, mongooses and cats were rarely caught, but outside the col-

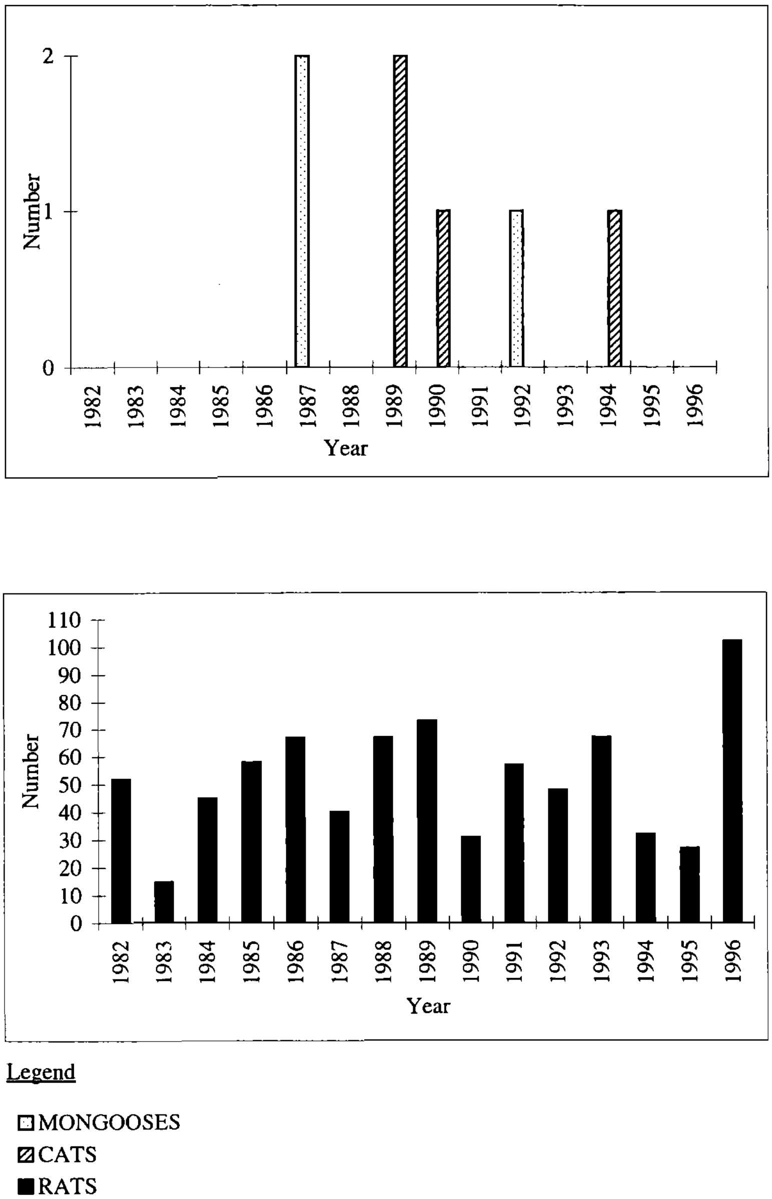

FIGURE 5. Numbers of predators caught within the ‘Ua‘u colony.

ony the catch increased. There has been no observed predation from cats or mongooses in the years when these predators were caught in the colony. This suggests that the few mongooses and cats that enter the ‘Ua‘u colony are trapped before they are able to cause harm to the ‘Ua‘u.

DISCUSSION

Effects of Introduced Predators

Significant differences in nesting activity and nesting success suggest that predator control trapping has positive effects on the ‘Ua‘u. Except for 1994 and 1996 in which the unprotected sites had a higher nesting activity and nesting success rates, respectively, all other years showed higher activity or success in protected sites (Table 1).

The fact that nesting activity and nesting success rates from within and outside areas subject to trapping did not differ significantly in some years is not surprising. Mongooses and cats in areas without traps (unprotected burrows) may

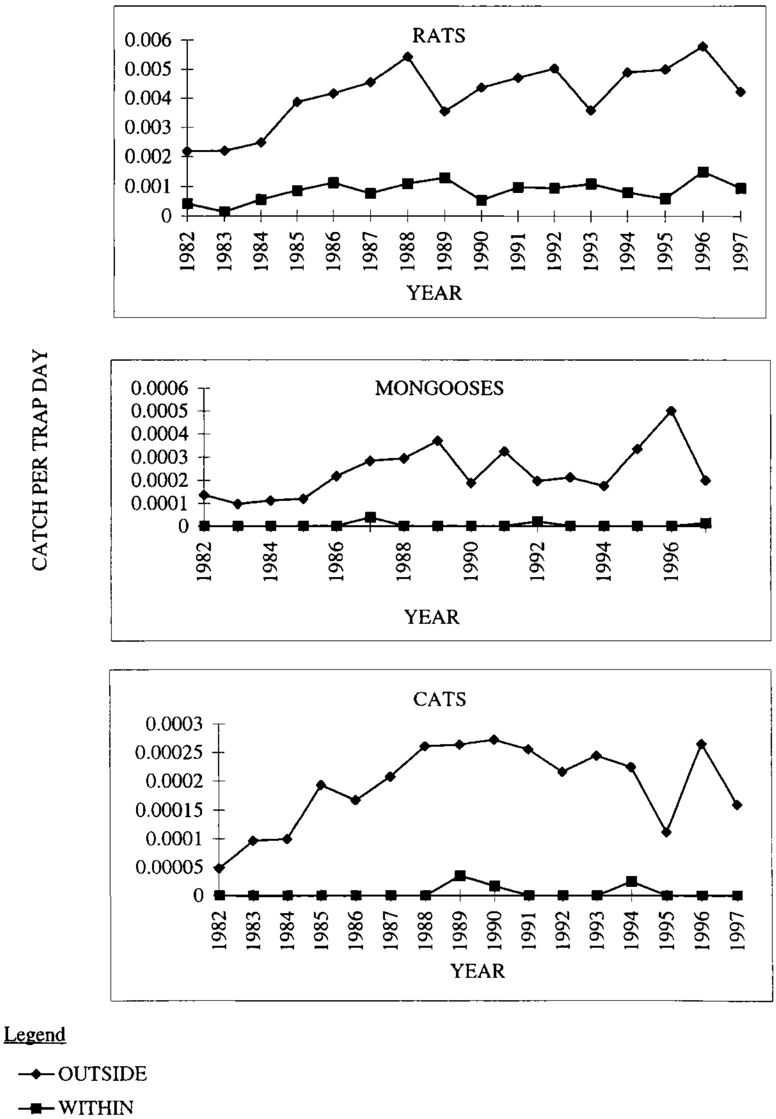

FIGURE 6. Yearly rat, mongoose, and cat catches from outside and within the ‘Ua‘u colony.

travel into areas with traps and may subsequently be captured. Also, numbers of predators near the ‘Ua‘u colony may be low since removal efforts have been continuous for 15 years. Existing traps may be capturing predators that would otherwise travel to untrapped areas.

The higher catch of mongooses and cats at lower elevations indicates that these predators will continue to pose a threat to the high-elevation ‘Ua‘u colonies (Hu et al. *this volume*). Simons (1983) found that one mongoose or one cat could prey upon large numbers ‘Ua‘u. It is possible for mongoose or cat predation to go undetected in the ‘Ua‘u colonies. Areas where eggshell fragments are found should be thoroughly examined for mongoose or cat presence.

There is continuous catch of cats and mongooses and evidence of these predators breeding in lower elevations (Hodges 1994). These adjacent areas may be acting as a source habitat for predators and that our ‘Ua‘u colony may be a sink (Pulliam 1988, Howe et al. 1991). The source for predators from areas outside the park is high. Maui County Humane Society annual reports (unpubl. data) from 1992, 1993, and 1995 show that almost 6,000 cats and about 3,000 dogs were received each year. Of six possible location sources throughout Maui, 34% of the cats and 44% of the dogs came from the area adjacent to the park.

It is conceivable that cats, and possibly mongooses, travel far into the ʻUaʻu nesting area. Rood (1986) cites the home range of mongooses in Fiji as 0.39 km^2 where population densities were 50 mongooses per km^2. Apps (1986) found that the home range of cats was 0.62 to 1.50 km^2 on Marion Island, South Africa, where population densities were 4 to 5 cats per km^2. Future research may be needed to determine the home range of cats and mongooses at Haleakalā.

Feral cats are frequently sighted throughout the park (Haleakalā National Park, unpubl. data). Cats are captured, but some appear evasive to current predator control techniques. Field personnel continuously report cat tracks and droppings in areas with traps. This indicates that cats persist within the park and continue to threaten the ʻUaʻu population. Small-scale predation can be detrimental to endangered bird populations such as the ʻUaʻu (Karl and Best 1982, van Reusenburg and Bester 1988, Rodriguez-Estrella et al. 1991). Cats from these studies severely decreased populations of nesting birds.

It is clear that trapping is only partially effective on rats since rat predation is still being detected. Rodent populations persist in the ʻUaʻu colony and appear to have both direct and indirect negative effects on reproductive success. Rats appear to have preyed upon eggs and to have disturbed breeding adults. On Midway Atoll, rat predation on Bonin Petrel eggs caused a dramatic decline in the breeding population (Seto and Conant 1996). Arthropods and vegetation in the ʻUaʻu colonies, many of which are endemic, are prominent diet items and allow rats to persist at higher elevations (F. Cole et al., unpubl. report). Healthy populations of house mice (*Mus domesticus*) exist at elevations equivalent to the ʻUaʻu colony throughout the year. Together with the persistent rat population, these rodents serve as prey bases for mongoose and cat populations (Stone 1989). This allows for the potential existence of mongooses and cats in the ʻUaʻu colony, even after the ʻUaʻu have left from the Haleakalā colony for the season. Seto and Conant (1996) found that control of rats with a rodenticide significantly suppressed rat numbers on Midway Atoll. This decreased the instances of rat predation on eggs and increased Bonin Petrel breeding success. In January 1997, diphacinone (an anticoagulant) was placed in the ʻUaʻu colony to lower rat populations. The effectiveness of this toxicant needs to be examined.

Other Impacts on ʻUaʻu

The boundary fence protects Haleakalā's ecosystem from ingress of goats and pigs. Unprotected areas had higher nesting success in 1994, and nesting activity in 1996. This may be attributed to habitat regeneration. Revegetation and soil retention has improved within the park's boundary since removal of feral ungulates (Haleakalā National Park, unpubl. data). It is therefore conceivable that ʻUaʻu benefit from overall habitat protection. Feral ungulates no longer pose a threat by collapsing nests. Soil retention may make for more suitable habitat for these burrowing birds. Additionally, the boundary fence prevents dogs from entering the colony and preying upon ʻUaʻu.

The boundary fence has, unfortunately, caused ʻUaʻu mortalities since 1976. The bulk of the mortalities occurred from 1986 to 1988. Fences are routinely inspected for breaks, thus making detection of fence-caused mortality very thorough. Most of the ʻUaʻu caught were found impaled on the barbed wire portion of the fence. Beginning in 1987, Haleakalā National Park crews removed these two top strands of barbed wire in all the areas where ʻUaʻu were snagged. This reduced the fenced-caused mortality of ʻUaʻu to almost zero (Haleakalā National Park, unpubl. data). Although ʻUaʻu mortalities occur because of the fence, new nests that produce young each year are constantly found. Additionally, the number of total nests have increased from 659 in 1990 to 986 in 1996. Goat herds as large as 50 have been sighted in the southwestern ʻUaʻu colony outside the park as recently as January 2000. If fences are removed to prevent further mortality, goats and pigs would return to the park and reverse 10 years of ecosystem recovery in the crater. Larger predators such as lost hunting dogs might enter the park and through breaks in the fence devastate the main ʻUaʻu colony.

Our data found that few ʻUaʻu were killed by owls. Harris (1970) found owls to be prominent predators on the Galápagos Dark-rumped Petrel. The native Short-eared Owl (*Asio flammeus sandwichensis*), known by its Hawaiian name Pueo, are frequently sighted throughout the park and appear to be increasing. Sightings of the introduced Barn Owl (*Tyto alba*) in the park have increased (Haleakalā National Park, unpubl. data). Owl predation may have been minimal in the past because the owl population consisted only of the crepuscular Pueo. Predation upon the nocturnally active ʻUaʻu by owls may increase as the nocturnally active Barn Owl population expands.

A recent threat to the Haleakalā ecosystem is the increasing population of axis deer on Maui. Recent observations and high-end estimates put the axis deer population at up to 10,000 on East Maui (Maui Axis Deer Group, pers. comm.). The park's fences are too low to prevent the deer from jumping into the park. However, higher fences may result in a significant increase in ʻUaʻu mortality as observed in the past. If this deer becomes established in the park, its destructive activities will be far worse than feral goats. Current axis deer management at Haleakalā includes monitoring of deer during fence inspections and trapline maintenance. Sightings inside the park's fence are followed up by ground or helicopter removal of the deer.

A dynamic system of factors influences the survival and breeding success of the endangered Hawaiian Dark-rumped Petrel. Without an active management program, ʻUaʻu populations would be subjected to heavy impacts by predators such as cats, mongooses and dogs, and by habitat destruction by ungulates. The surviving Maui ʻUaʻu populations probably exist because of the high-elevation nesting environment which may be too hostile for most of the introduced predators to endure.

Current management efforts to control predators, remove ungulates, and maintain the boundary fences have reduced predation and provided for habitat recovery. However, predation will persist and the habitat will always be threatened by ungulates.

A persistent population of rats serves as a prey base for cats and mongooses, and appears to have negative effects on ʻUaʻu breeding success. Since traps have not eradicated rats in the ʻUaʻu colony, increased use of rodenticides may be needed to remove this prey base in order to deprive mongooses and feral cats of their primary food source. Rodent removal may benefit not only the ʻUaʻu, but other native birds, endemic arthropods, and native vegetation at Haleakalā.

Habitat destruction is the primary threat to all of Hawaiʻi's remaining native biota (Stone 1989). The State of Hawaiʻi's increasing human population and associated development, the constant influx of new alien species, and the spread of the most aggressive aliens have accelerated habitat loss for these endangered species.

MANAGEMENT RECOMMENDATIONS

The ultimate management objective for the ʻUaʻu population at Haleakalā is to ensure survival of the species. Simons (1984) emphasized the importance of adult survival for population growth. Our findings show that continual management of ʻUaʻu is necessary for species survival.

1. Predator control is necessary to keep predator populations low. The use of traps and approved toxicants such as diphacinone are means of predator control. To avoid a detrimental dietary shift from rats to ʻUaʻu, it is extremely important to control cats and mongooses while controlling rats. A multispecies toxicant may be useful in decreasing the labor-intensive live-trapping program.
2. Continual monitoring of ʻUaʻu nests is necessary to determine changes in nesting activity and success. Monthly monitoring using toothpicks is an inexpensive and valid means of determining nesting activity but is also labor-intensive.
3. Maintaining feral animal control fences is necessary to keep ungulates from reentering the recovering nesting habitat. Special modifications to select portions of the existing boundary fences may be required due to the newly emerging axis deer threat.
4. Searching other islands for productive nesting colonies of Hawaiian Dark-rumped Petrels is necessary for species survival.

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